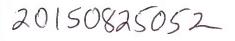
# REPORT DOCUMENTATION PAGE

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14. ABSTRACT				
We pioneering infrared power generation as a renewable and sustainable source of energy available day and night and non dangerous to humans				
and machines. We have studied the basic mechanisms, discovered an electric contribution that enables the increase of the efficiency. We have submitted one manuscript with the first findings. More will be discovered in the research initiated by this grant. We have trained seven students				
and disseminated findings and knowledge to technical, academic and broad audience.				
and disseminated findings and knowledge to technical, academic and broad addictice.				
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power generation.				
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# Infrared power generation: study in an insulated compartment Office of Naval Research – Award # N000141410378

Technical (including Workshop) and Financial Final Report – August 14, 2015
PI: Giovanna Scarel, and Co-PI: Brian C. Utter (James Madison University-JMU)
Period of Activity: May 1, 2014 – August 14, 2015

Office of Naval Research (ONR) – The sea warfare and weapons department (Code 33)

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# Power Bille generator electeors

Fig. 1. Illustration of the PG devices in the toward and away configurations with colored gaffer tape placed on the surface of the PG device illuminated by the IR radiation. The alternation of conductive (e.g. Cu) and insulating layers (e.g. AlO) in the capacitor-like PG device is visible.

# ONR Administrative/business contact: Mr. Rob

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# **OBJECTIVE:**

Infrared power generation (IRPG) consists of shining infrared (IR) radiation on a power generator (PG) device and collecting a usable voltage. The PI and Co-PI are actively pioneering the effort of understanding and implementing IRPG. <u>Scientifically</u>, the primary objective of this Project is to unveil the mechanisms alternative to the Seebeck effect contributing to voltage production in IRPG. This task implies establishing and assessing the equivalence or lack thereof among radiative heat transfer, on one hand, and convective and conductive heat transfer, on the other. Some possible consequences of such an equivalence or lack thereof in the fields of device physics, astronomy and geology, biology and medicine and art, are discussed. <u>Technologically</u>,

the primary objective of this Project is to initiate the exploitation of voltage production mechanisms in IRPG alternative to the Seebeck effect to enhance the power output of PG devices. <u>Educationally</u>, this Project aims at training undergraduate students in energy-related science and technology relevant for the U.S. Navy and disseminating knowledge and awareness to a broad audience. <u>Significance and Future Naval Relevance</u>: The method to harvest radiation used in IRPG could be extended to other electromagnetic radiation. Broaden the spectrum of the usable electromagnetic spectrum would greatly contribute to the renewable and sustainable energy sources available to humankind. In particular, low frequency and low power radiation is important for applications on ships, satellites, cars, personal backpacks, and, more generally, where non-dangerous energy is needed at all hour of the day, independent of weather condition.

A no-cost extension of the research project-ONR Award # N000141410378 to September 30, 2015 was obtained on March 25, 2015. The Workshop "Infrared radiation, Thermoelectricity and Chaos", included in the project's activities, took place on June 17, 2015 at JMU (from now the IRTC Workshop) and the outcome is summarized in this Report.

#### TECHNICAL REPORT.

#### Scientific achievements.

Infrared radiation can be harvested and transformed into usable electricity using a PG device similar to that illustrated in Fig. 1. This phenomenon is IRPG, pioneered by the PI and Co-PI. Our study of the available literature and discussions with the scientists and engineers invited to the IRTC Workshop, clearly point out that our experimental set up and outcome are unique

(•) Experimental set-up: The PG device we used for IRPG is a thermoelectric power generator 07111-9L31-04B by Custom Thermoelectric Inc. The device works according to the Seebeck effect:  $\Delta V = -S\Delta T$ , where  $\Delta V(t)$  is the voltage difference,  $\Delta T(t)$  the temperature difference between the two faces, and S the Seebeck coefficient. Because of its layered structure consisting of a sequence of conductive and insulating layers, as described in Fig. 1, the PG device also behaves as a capacitor [1]. We used a sample holder made of black anodized aluminum to complete the capacitor structure of the PG device in both the away and the toward configurations. In the away configuration we keep the illuminated face free from contact with the sample holder, while in the toward configuration we place the illuminated face in contact with the sample holder.

To understand the behavior in time of the IR radiation, we characterized the radiation's power P(t), using a power-meter sensor Coherent PowerMAX RS PS19. We revealed sinusoidal oscillations related to the temperature fluctuations in the closed sample compartment in which the measurements were performed [1].

To better characterize the *entropic* contribution, related to convective and conductive heat transfer, we also performed measurements by activating the PG device with a  $100~\Omega$  resistor through a power supply providing 3.2~V and 0.02~A [1].

(•) <u>Data analysis</u>: We measured as a function of time t the voltage difference  $\Delta V(t)$  and temperature difference  $\Delta T(t) = T_{IR}(t) - T_{no-IR}(t)$  between the illuminated and the non-illuminated faces of the PG device. We investigated data in (i) the 400 seconds immediately after starting the illumination, and (ii) the 30-60 hours thereafter. (i) In the rise of  $\Delta V(t)$  in the 400 seconds immediately after starting the illumination, we identify two components distinguished

by their rate of increase. The faster component is solely detected in  $\Delta V(t)$ . The slower component, detected in  $\Delta V(t)$ ,  $T_{IR}(t)$ ,  $T_{no-IR}(t)$  and  $\Delta T(t)$ , rises at a rate similar to that of  $T_{IR}(t)$ ,  $T_{no-IR}(t)$ , and  $\Delta T(t)$ . (ii) In the 30–60 hours after starting the illumination,  $\Delta V(t)$  often exhibits small non-periodic instabilities related to the time-scale of the sinusoidal oscillations of the power P(t) of the IR radiation but with unpredictable phase. These instabilities are absent in  $\Delta T(t) = T_{IR}(t) - T_{no-IR}(t)$  and are named hyperbolic instabilities. We show that the hyperbolic instabilities are the solution of a nonlinear equation. We have reported the details of the data analysis in our recently submitted manuscript [1]. We plan on showing explicitly that the hyperbolic instabilities are related to P(t) through the behavior in time and space of  $\sigma(\mathbf{z},t)$ , the density of charges on the illuminate face of the PG device acting as a capacitor. The variable  $\mathbf{z}$  in  $\sigma(\mathbf{z},t)$  is space defined on a two-dimensional surface treated as a complex plane. In Fig. 2 we depict a snapshot of  $\sigma(\mathbf{z},t)$  obtained in our preliminary study.

(•) Results: At first glance, the energy transfer from low power IR radiation to the PG device would be attributed to convective and conductive heat transfer, i.e. to an *entropic* contribution. Instead, we found that also an *electric* contribution is involved. The *electric* contribution is related to electromagnetic nature of the IR radiation. We unveil the *electric* contribution in the component rising faster in  $\Delta V(t)$  in the 400 seconds immediately after starting the illumination, exhibiting the hyperbolic instability in the 30–60 hours thereafter, and uniquely appearing in  $\Delta V(t)$ . We detect the *entropic* contribution in the components rising slower and contributing to  $\Delta V(t)$ ,  $T_{IR}(t)$ ,  $T_{no-IR}(t)$ , and  $\Delta T(t)$ . Interestingly, with low power IR radiation we find that the *electric* contribution dominates over the

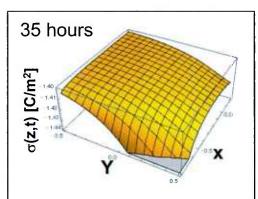


Fig. 2. Charge density  $\sigma(\mathbf{z}, t)$  on the surface of the PG device 35 hours after starting the illumination with low power IR radiation.

entropic contribution. This finding has significant consequences for the technological applications of IRPG. When the electric contribution dominates, the capacitor-type behavior of the PG device, described in Fig. 1, enables the voltage produced to be doubled by simply placing piece of black-colored gaffer tape on the illuminated face [1]. In addition, our preliminary data indicate that the jump in the voltage increases as a function of incidence angle  $\theta_0$  of the IR radiation on the PG device at the rate of 9  $10^{-3}$  mV/ $_{\odot}$ . Furthermore, our test experiments clearly show that the voltage can be increased also placing two PG devices in series and we have good reasons to believe that also in this case the voltage increases with  $\theta_0$ . Preliminary results on the gain in voltage production  $\Delta(\Delta V)$  are summarized in Fig. 3.

After defining the best device-radiation geometry, we will proceed with systematic experiments on the effects of PG devices in series, current production and effects of radiation power, within the research project-ONR Award # N000141512158 (March 2015-March 2017).

On the other hand, we will soon submit a new grant proposal to support the effort of demonstrating that the hyperbolic instabilities in  $\Delta V(t)$  are related to P(t) through the behavior in time and space of  $\sigma(\mathbf{z},t)$ .

(•) <u>Conclusions</u>: Because of the lack of coupling between the *electric* and *entropic* contributions to energy transfer from IR radiation to a PG device, we conclude that radiative heat transfer, corresponding to the *electric* contribution, and convective and conductive heat transfer, corresponding to the *entropic* contribution, are non-equivalent. In IRPG, such non-equivalence enables multiple ways to increase the voltage produced, e.g., by properly sandwiching the PG device with black gaffer tape, or with other PG devices, or by choosing the proper incudence angle  $\theta_0$  with the IR radiation. After defining the  $\theta_0$  that maximizes voltage production, we will systematically investigate the effects of PG devices in series and of radiation power on voltage and current production within the research project-ONR Award # N000141512158 (March 2015-March 2017). In a broader context, the consequences of the lack of equivalence between

radiative heat transfer, on one hand, and convective and conductive heat transfer, on the other, can be summarized as follows. In astronomy and geology, low frequency and low power radiation must be considered for their interaction with a planet's magnetic field. In biology and medicine low frequency and low power radiation should be expected to interact with the nerve system, where cells are similar to coaxial cables with the structure of a capacitor. In art, low frequency and low power radiation should be considered affecting performance of colored glass windows environments with low average temperature [2].

#### Educational achievements.

The <u>educational results</u> achieved are as follows:

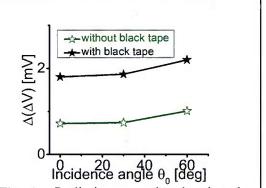


Fig. 1. Preliminary results showing the gain in voltage production  $\Delta(\Delta V)$  upon starting the illumination of the PG device with low power IR radiation as a function of incidence angle  $\theta_0$  and presence or absence of the black-colored gaffer tape.

(•) <u>Student training</u>: In Summer 2014 two undergraduate students (Graham P. Gearhart and Kyle A. Britton) performed work with the PI and Co-PI. These students were entirely supported by ONR Award # N000141410378. Three other students were involved: Justin M. Kaczmar, Harkirat S. Mann, and Brian N. Lang. In Fall 2014 and Spring 2015, more students joined the team: Zachary J. Marinelli, Aidan L. Gordon, Yosyp Schwab, and Tara R. Jobin (partially supported by ONR Award # N000141410378). Supervised by the PI, Co-PI, and technical personnel at JMU, the students assembled the insulated compartment, interfaced the experimental set-up with the electronic data collection system, and finally collected and analyzed the experimental data. The students used the machine shops at JMU, were involved in the intellectual effort of modeling and understanding the data, and presented the results at various venues. The student's efforts were rewarded by their inclusion in the list of authors of the publication reporting most of the recent findings [1]. Five students actively participated to the IRTC Workshop.

In Spring 2015 Kyle A. Britton was accepted into the Naval Research Enterprise Internship Program – NREIP. He spent Summer 2015 at the Naval Air Weapons Station China Lake. One

day he amazed his supervisor because he knew what a soliton is. Kyle became familiar with solitons while participating to the research activity on IRPG in Summer 2014.

- (•) <u>Academic outreach objectives</u>: In Fall 2014, the PI used the concepts and findings of the research project-ONR Award # N000141410378 in her course on "Thermodynamics and Statistical Mechanics" (PHYS 380). Finding signs of distinction between the electric and entropic contributions to energy transfer supported the PI's effort to approach thermodynamics and statistical mechanics through a description based on couples of conjugated variables such as entropy S and temperature T, charge q and voltage V, and exact differentials. The PI explored the consequences of the lack of equivalence between the electric and entropic contributions to energy transfer to better understand Kirchhoff's law of thermal radiation and radiative heat transfer [3, 4], and, more in general, the interaction between radiation and matter in "Modern Optics" (PHYS 420) in Spring 2015. Finally, in Fall 2015 the PI will illustrate concepts such as equilibrium, stability and nonlinearity providing examples from the research project-ONR Award # N000141410378.
  - (•) **Broader outreach objectives**: Two main objectives were achieved:
- $\rightarrow$  The PI illustrated some of the findings of the research project-ONR Award # N000141410378 in:
- (i) an event at JMU for alumni and their families to showcase the performances of current JMU's faculty members [5].
- (ii) an event organized by the Mount Jackson Rotary Club, Mount Jackson (VA), on August 4, 2015. Similar events might likely take place in the near future.

In both cases the PI's presentation was well received and effective in disseminating the awareness of the U.S. Navy's interest in alternative sustainable energy programs.

→ The PI enriched her program to introduce physics to elementary school children in a program entitled "Power from crystals" with ideas, concepts, and goals of the research project-ONR award # N000141410378. The program aims at attracting the attention of young students and future workforce to Materials Physics and Statistical Mechanics, by introducing them to the wide opportunities available for them in careers in Science and Technology, as well as illustrating the useful skills they can gain to serve the U.S. Navy.

# Bibliography.

- [1] A.L. Gordon, Y. Schwab, B.N. Lang, G.P. Gearhart, T.R. Jobin, J.M. Kaczmar, Z.J. Marinelli, H.S. Mann, B.C. Utter, and G. Scarel, "Decoupling the electrical and entropic contributions to energy transfer from infrared radiation to a power generator". Submitted to J. Renewable Sustainable Energy on 7/29/2015.
- [2] G. Scarel, "Infrared power generation". Mount Jackson Rotary Club, Mount Jackson (VA), August 4, 2015.
- [3] P.-M. Robitaille, *Kirchhoff's law of thermal emission: 150 years*, Progress in Physics 4, 3-13 (2009).
- [4] T. Inoue, M. De Zoysa, T. Asano, and S. Noda, *Realization of dynamic thermal emission control*, Nature Materials 13, 928-931 (2014).
- [5] G. Scarel, From JMU to the World: embracing the need of new energy sources, Madison Trust Event, President's Board Room, JMU; Harrisonburg (VA), November 14, 2014.

# Publications acknowledging research project-ONR Award # N000141410378.

- (1) A.L. Gordon, Y. Schwab, B.N. Lang, G.P. Gearhart, T.R. Jobin, J.M. Kaczmar, Z.J. Marinelli, H.S. Mann, B.C. Utter, and G. Scarel, "Decoupling the electrical and entropic contributions to energy transfer from infrared radiation to a power generator". Submitted to Journal of Renewable and Sustainable Energy on July 29, 2015.
- (2) H.S. Mann, B.N. Lang, Y. Schwab, J.-P. Niemelä, M. Karppinen, and G. Scarel, "Infrared and thermoelectric power generation in thin atomic layer deposited Nb-doped TiO<sub>2</sub> films". J. Vac. Sci. Technol. A **33** 01A124 (2015).
- (3) H.S. Mann, Y. Schwab, B.N. Lang, J.L. Lancaster, R.J. Parise, and G. Scarel, "Effective thermoelectric power generation in an insulated compartment". World J. Cond. Matter Phys. 4, 153-165 (2014).

# Scientific presentations acknowledging research project-ONR Award # N000141410378. (•) PI:

- (1) G. Scarel, "Infrared power generation". Mount Jackson Rotary Club, Mount Jackson (VA), August 4, 2015.
- (2) G. Scarel, "Infrared power generation: fundamental understanding, applications and benefits". IRTC Workshop.
- (3) G. Scarel, "Infrared power generation: physics and applications". U.S. Naval Research Laboratory; Washington (DC), April 16, 2015.

# (•) Students:

- (4) T.R. Jobin, J.M. Kaczmar, B.C. Utter, and G. Scarel, "Voltage hyperbolic instablities from infared radiation". (Poster) 2015 Summer Research Symposium, JMU; Harrisonburg (VA), July 30-31, 2015.
- (5) <u>G.P. Gearhart</u>, B.C. Utter, and G. Scarel, "*Tape-influenced infrared and thermal power generation*". (Oral) 2015 Undergraduate Research Symposium in Physics; JMU; Harrisonburg (VA), March 21, 2015, and 93<sup>th</sup> Annual Meeting of the Virginia Academy of Science, JMU; Harrisonburg (VA), May 21-23, 2015.
- (6) <u>A.L. Gordon</u>, B.C. Utter, and G. Scarel, "Determining a mathematical model for a voltage-induced, exclusively temporal soliton". (Oral) 2015 Undergraduate Research Symposium in Physics; JMU; Harrisonburg (VA), March 21, 2015, and 93<sup>th</sup> Annual Meeting of the Virginia Academy of Science, JMU; Harrisonburg (VA), May 21-23, 2015.
- (7) <u>K.A. Britton, J.M. Kaczmar, Y. Schwab, H.S. Mann, B.N. Lang, B.C. Utter, and G. Scarel, "Angular dependence of infrared power generation".</u> (Oral) 2014 Summer Research Symposium, JMU; Harrisonburg (VA), July 29-30, 2014.
- (8) <u>G.P. Gearhart,</u> J.M. Kaczmar, H.S. Mann, B.N. Lang, K.A. Britton, B.C. Utter, and G. Scarel, "*Infrared source and thermoelectric device trends in infrared power generation*". (Poster) 2014 Summer Research Symposium, JMU; Harrisonburg (VA), July 29-30, 2014.
- (9) <u>H.S. Mann</u>, <u>B.N. Lang</u>, Y. Schwab, J.-P. Niemelä, M. Karppinen, and G. Scarel, "Infrared and thermoelectric power generation in thin ALD thermoelectric films". (Oral) 2014 Summer Research Symposium, JMU; Harrisonburg (VA), July 29-30, 2014, and AVS 61<sup>th</sup> International Symposium; Baltimore (MD), November 9-14, 2014.

#### IRTC WORKSHOP REPORT.

The IRTC Workshop was one of the most important activities of the research project-ONR award # N000141410378. The event was organized by the PI and Co-PI together with Mr. Benjamin T. Delp, Director of the JMU Research Development and Promotion Office. The Workshop featured two international speakers. Prof. Giulio Casati of Italy spoke about Conservation laws, symmetry breaking and control of the heat current. Prof. Francisco Javier Gonzalez Contreras of México described Seebeck nanoantennas for solar energy harvesting. Three speakers represented the U.S.A. academic world. Prof. Gabriel A. Rincón-Mora of the Georgia Institute of Technology, presented Microwatt CMOS harvesters. Amirtharajah of the University of California-Davis, discussed Powering systems from ambient energy sources. Finally, Prof. S. Joseph Poon of the University of Virginia, presented Practical realization of ZT>1 from the materials perspective. The business and entrepreneurial world was represented by Dr. Ronald J. Parise of Parise Research Technologies, who introduced The Nighttime solar cell<sup>®</sup>: infrared energy to deep space. Dr. Joseph R. Blandino of the Virginia Military Institute, and Dr. David J. Lawrence of JMU, presented a poster on Transient response of a thermoelectric generator subjected to spatially non-uniform heating: implications for heat and IR sensing applications. In her presentation, the Dr. G. Scarel (PI) explained the connection among the words in the IRTC Workshop's title, justified the selection of the speakers, and illustrated the current knowledge on IRPG.

Two posters were presented by JMU Physics students Graham P. Gearhart and Brian N. Lang. Graham presented "Infrared source and thermoelectric device trends in infrared power generation", while Brian discussed "The interaction between current and infrared radiation". The JMU Physics students Justin M. Kaczmar, Zachary J. Marinelli and Tara R. Jobin joined the event by helping in the logistics, asking questions during the sessions and actively networking.

Dr. Brian C. Utter (Co-PI) and Mr. Lynn J, Petersen (ONR) chaired the morning and the afternoon sessions, respectively. Dr. Yvonne R. Harris, JMU's vice Provost for Research and Scholarship, and Mr. Lynn Petersen opened the event in the morning and addressed the final remarks in the afternoon, respectively.

The IRTC Workshop was funded by the ONR award # N000141410378. Additional funding, used to support the logistics, pay the honorarium for Dr. J.R. Blandino and partially that of Prof. Prof. F.J. Gonzalez, was provided by the JMU 4-VA Consortium and The JMU Madison Trust—Fostering Innovation and Strategic Philanthropy. The international speakers (Prof. G. Casati and Prof. F.J. Gonzalez) were mainly funded by ONR Global-London (UK).

The IRTC Workshop revealed that IRPG explores a rather unknown topic in a unique experimental setting. Specifically:

- (•) **F.J. Gonzalez**: excites a PG device exploiting Joule heating, i.e. an *entropic* contribution, derived from an electric current activated in an antenna by the IR radiation. His research does not explore the direct effects of radiation, i.e. of the *electric* contribution, on voltage output as we do in IRPG.
- (•) **R.J. Parise**: uses IR radiation as a mean to carry heat to deep space which, acting as a heat sink, facilitates the creation of a temperature difference in a PG device.
- (•) **D.J. Lawrence and J.R. Blandino**: use high power fiber optics to activate a PG device. Their results are above the power range of IRPG.
- (•) G. Casati: pointed out that the term "soliton" was improperly used by PI in her presentation, thus underlining that the hyperbolic instability highlighted in the briefing on IRPG is a new entity.

#### FINANCIAL REPORT.

# Expenditures.

- (•) Stipends:
- → Brian C. Utter (Co-PI, Associate Professor, JMU, Department of Physics and Astronomy), August 2014, \$ 929.00
- → **Graham P. Gearhart** (Undergraduate student, JMU, Department of Physics and Astronomy), May 27 August 2 2014, \$8.50/hour, \$4,000.00
- → **Kyle A. Britton** (Undergraduate student, JMU, Department of Physics and Astronomy), May 27 August 2 2014, \$ 8.50/hour, \$ 4,000.00
- → **Tara R. Jobin** (Undergraduate student, JMU, Department of Physics and Astronomy), July 1 July 15, 2015, \$ 8.50/hour, \$ 475.00
  - (•) Taxes:

FICA: \$ 749.83

- (•) Travel:
- → Hotel for G. Scarel's trip to Alexandria (VA) Naval Research Laboratory (NRL) on April 16, 2015: \$ 317.56. (Scientific visit to collaborators and research presentation).
- → Car rental for G. Scarel and B. Utter trip to Alexandria (VA) NRL on June 11, 2015: \$ 81.76. (Planning meeting with ONR Program officer and NRL collaborators).

# (•) Miscellaneous:

- → Shipping samples to NRL April 23, 2015: \$ 3.64. (Samples for Ultraviolet-Visible spectroscopy characterization to Dr. Joshua Caldwell).
- → Shipping Software to Leesburg (VA) July 6, 2015: \$ 5.19. (Software to student Aidan Gordon).
- $\rightarrow$  Wolfram-Mathematica software: \$ 158.48. (Software for preliminary test on modeling  $\sigma(\mathbf{z},t)$ ).

# (•) IRTC Workshop-honoraria:

- → Prof. Giulio Casati: \$ 200.00
- → Prof. Francisco Javier Gonzalez Contreras: \$87.54
- → Prof. Gabriel A. Rincón-Mora: \$ 2,500.00
- → Prof. Rajeevan Amirtharajah: \$ 2,500.00
- $\rightarrow$  Prof. S. Joseph Poon: \$ 1,500.00
- $\rightarrow$  Dr. Ronald J. Parise: \$ 2,500.00
- → Dr. David J. Lawrence: \$ 400.00

# (•) Indirect cost:

 $\rightarrow$  \$ 9,592.00

# Other support.

- (•) Thomas F. Jeffress and Kate Miller Jeffress Memorial Trust, January 1, 2012 December 31, 2014: "Role of polarization of broadband infrared radiation in the heat recovery mechanism involved in the excitation of radiative polaritons in thin oxide films". PI: G. Scarel (JMU). Grant # J-1053. (Student support).
- (•) 4VA Collaborative Research Project 2013-2014, January 1, 2014 December 31, 2014: "Effects on thermoelectric power generation of the source-device distance". PI: G. Scarel (JMU). Co-PI: Rosa A. Lukaszew (College of William&Mary). (Student support).

- (•) 4VA Collaborative Research Project 2014-2015: "Giving to JMU international visibility in infrared power generation and its link to non-linear phenomena". PI: G. Scarel (JMU). Co-PIs: Rosa A. Lukaszew (College of William&Mary) and Brian C. Utter (JMU). (IRTC Workshop support).
- (•) JMU Madison Trust—Fostering Innovation and Strategic Philanthropy Innovation Grant 2015, November 14, 2014: "From JMU to the World: embracing the need of new energy sources". (Student and IRTC Workshop support).
  - (•) JMU Department of Physics and Astronomy. (Student, equipment and facility support).

# ATTACHMENTS.

- 1) IRTC Workshop plan
- 2) Posters (2)
- 3) Papers (3)
- 4) Presentations (7)
- 5) Official acceptance of the no-cost extension